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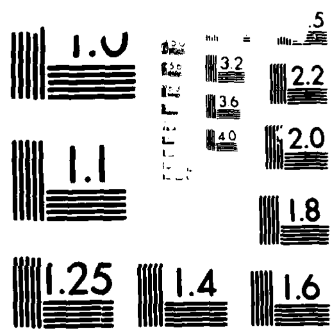
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FRONT SURFACE PYROMETER

Marvin Morrison Hoffman
Los Alamos Technical Associates, Inc.
P. O. Box 410
Los Alamos, NM 87544-0410

8 March 1985

Technical Report

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Principal users of the Tri-Service Thermal Flash Test Facility (TFTF) were surveyed to determine their perceived need for noncontact front surface temperature measurements on specimens being tested at the facility. Performance specifications and operational capabilities which define a radiation pyrometer system satisfactory for use at TFTF were developed from the results of this survey.

All of the principal specifications were satisfied by a long waveband infrared (8 - 11.5 um) pyrometer, marketed by Land Instruments Inc., Tullytown, PA for industrial applications, which was modified by the manufacturer to meet TFTF time response requirements.

The pyrometer was further modified by the addition of a water-cooled radiation channel to restrict the instrumental field of view to a size compatible with the space available in the test chamber.

Tests of the radiation pyrometer were performed at the TFTF with a high emmissivity

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19. ABSTRACT (Continued)

copper specimen. The tests show good correlation between front surface temperatures measured with the pyrometer system and back surface temperatures measured with thermocouples when allowance is made for temperature gradients generated in the specimen plate.

Preliminary tests with a low emmissivity specimen show that test chamber background may be a serious problem for temperature measurements on highly reflective surfaces.

A-1

Conversion factors for U.S. customary to metric (SI) units of measurement.

To Convert From	To	Multiply By
angstrom	meters (m)	1.000 000 × E − 10
atmosphere (normal)	kilo pascal (kPa)	1.013 25 × E + 2
bar	kilo pascal (kPa)	1.000 000 × E + 2
barn	meter² (m²)	1.000 000 × E − 28
British thermal unit (thermochemical)	joule (J)	1.054 350 × E + 3
cal (thermochemical)/cm²§	mega joule/m² (MJ/m²)	4.184 000 × E − 2
calorie (thermochemical) §	joule (J)	4.184 000
calorie (thermochemical)/g§	joule per kilogram (J/kg)*	4.184 000 × E + 3
curie§	giga becquerel (GBq)†	3.700 000 × E + 1
degree Celsius‡	degree kelvin (K)	$t_K = t°_C + 273.15$
degree (angle)	radian (rad)	1.745 329 × E − 2
degree Fahrenheit	degree kelvin (K)	$t_K = (t°_F + 459.67)/1.8$
electron volt§	joule (J)	1.602 19 × E − 19
erg§	joule (J)	1.000 000 × E − 7
erg/second	watt (W)	1.000 000 × E − 7
foot	meter (m)	3.048 000 × E − 1
foot-pound-force	joule (J)	1.355 818
gallon (U.S. liquid)	meter³ (m³)	3.785 412 × E − 3
inch	meter (m)	2.540 000 × E − 2
jerk	joule (J)	1.000 000 × E + 9
joule/kilogram (J/kg) (radiation dose absorbed)§	gray (Gy)*	1.000 000
kilotons§	terajoules	4.183
kip (1000 lbf)	newton (N)	4.448 222 × E + 3
kip/inch² (ksi)	kilo pascal (kPa)	6.894 757 × E + 3
ktap	newton-second/m² (N-s/m²)	1.000 000 × E + 2
micron	meter (m)	1.000 000 × E − 6
mil	meter (m)	2.540 000 × E − 5
mile (international)	meter (m)	1.609 344 × E + 3
ounce	kilogram (kg)	2.834 952 × E − 2
pound-force (lbf avoirdupois)	newton (N)	4.448 222
pound-force inch	newton-meter (N·m)	1.129 848 × E − 1
pound-force/inch	newton/meter (N/m)	1.751 268 × E + 2
pound-force/foot²	kilo pascal (kPa)	4.788 026 × E − 2
pound-force/inch² (psi)	kilo pascal (kPa)	6.894 757
pound-mass (lbm avoirdupois)	kilogram (kg)	4.535 924 × E − 1
pound-mass-foot² (moment of inertia)	kilogram-meter² (kg·m²)	4.214 011 × E − 2
pound-mass/foot³	kilogram-meter³ (kg/m³)	1.601 846 × E + 1
rad (radiation dose absorbed)§	gray (Gy)*	1.000 000 × E − 2
roentgen§	coulomb/kilogram (C/kg)	2.579 760 × E − 4
shake	second (s)	1.000 000 × E − 8
slug	kilogram (kg)	1.459 390 × E + 1
torr (mm Hg, 0° C)	kilo pascal (kPa)	1.333 22 × E − 1

* The gray (Gy) is the accepted SI unit equivalent to the energy imparted by ionizing radiation to a mass of energy corresponding to one joule/kilogram.

† The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.

‡ Temperature may be reported in degree Celsius as well as degree kelvin.

§ These units are not converted in DNA technical reports.

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SECTION 1

INTRODUCTION

Researchers using the Tri-Services Thermal Flash Test Facility (TFTF) are routinely confronted with the need to monitor specimen surface temperatures during testing. Thermocouples are normally used for these measurements even though several problems are associated with their use.

When high temperature gradients make the measurements taken beneath the surface unsatisfactory or when contact measurements are not possible because of surface melting or burning during testing, the desirability of a noncontact surface temperature measurement capability at the TFTF becomes apparent.

1-1 BACKGROUND.

Researchers at the TFTF have previously noted the need for noncontact measurements of specimen surface temperatures. The front surface pyrometer project was committed to the development of a radiation pyrometer system to meet this need. Radiation pyrometers are widely used in industry for rapid, reliable, remote temperature monitoring and process control.

Adaptation of industrial pyrometry equipment appeared to be the most effective approach to developing the capability for front surface temperature measurements at the TFTF.

The use of tungsten filaments as a heat source at this facility creates a difficult environment in which to use radiation pyrometry for collecting temperature data. Although these significant difficulties exist, this project was undertaken with the conviction that no insurmountable problems would prevent the development of a satisfactory radiation pyrometer for the TFTF.

1-2 OBJECTIVES AND SCOPE OF THE PROJECT.

The objectives of this project included the design and production of a prototype temperature measurement system specifically for use at the TFTF. Performance specifications for the system were determined by experimental requirements of projects currently under way or projected for the very near future. It was determined that the system would utilize electromagnetic radiation to make noncontact temperature measurements and that pyrometer technology offering the greatest operational flexibility and reliability would be emphasized.

Performance specifications were to be determined by a direct survey of frequent users of the TFTF. No aspect of the temperature measurement needs

of the thermal testing activities was excluded from the user survey. Although there were some individuals who, for security or proprietary reasons, could not give all details of expected values of peak fluxes, temperatures and time-rate-of-change of temperature, all available information was collected for use in selecting the radiation pyrometer specifications.

1-3 DEFINITION OF TERMS.

Some terms are used in this report which may not be completely familiar to all readers. The following definitions are included for the convenience of those who are interested and may not otherwise have the information easily available.

absolute temperature scale - a temperature measurement scale based on a division of the temperature difference between the ice point and boiling point of water at one atmosphere pressure into 100 equal intervals called degrees Kelvin or just Kelvins. The reference point of the absolute scale, also called the Kelvin scale, is the triple point of water which is defined to be 273.16°K.

angle of incidence - the angle formed by a line to a surface and the perpendicular to that surface.

blackbody - an ideal absorbing material, a surface which absorbs all incident radiation and reflects none.

blackbody radiation - electromagnetic radiation from an ideal surface of zero reflectivity. The rate of emission by a blackbody source is given by the Stefan-Boltzmann law, and the spectral energy distribution by Planck's radiation formula.

blocking filter - a radiation filter, sometimes called a band-stop filter which attenuates more or less uniformly all wavelengths in the selected band. A blocking filter attenuates from the band boundary to infinity.

cgs - the absolute metric system based on centimeters, grams mass, and seconds as the basic units.

calorie - the energy necessary to raise the temperature of one gram of water from 15°C to 16°C.

Celsius temperature scale	- a temperature scale based on 100 degrees between the ice point and boiling point of water and for which the triple point of water is defined to be 0°C. T(Celsius) = T(Kelvin) - 273.16.
emissivity	- ratio of flux radiated by a hot substance to the flux radiated by a blackbody at the same temperature.
Fahrenheit temperature scale	- a temperature scale defined by, degree Fahrenheit = 9/5 degree Celsius + 32.
field of view	- the area or solid angle which can be viewed through an optical instrument.
graybody	- an energy radiator having a blackbody energy distribution with the amplitude reduced by a constant factor over the entire spectrum.
infrared radiation	- electromagnetic radiation having wavelengths between approximately 1.0 and 500μm.
infrared pyrometer	- a radiation pyrometer which is sensitive to radiation in the infrared portion of the electromagnetic spectrum.
instrumental scale shape	- the functional relationship between surface temperature and the energy radiated by that surface in specific spectral regions.
Planck's radiation formula	- an analytic expression for the electromagnetic power radiated per unit area and unit wavelength by a surface at temperature, T, degrees Kelvin.
pyrometer	- a generic term for instruments for measuring thermal energy.
radiation thermometer	- an instrument for sensing radiation and converting it to an electrical signal proportional to the radiation flux.
reflectance	- the ratio of the reflected flux, either specular or diffuse, to the flux incident on a surface.

Stefan-Boltzmann law	- the total energy radiated from a blackbody is proportional to the fourth power of the absolute temperature.
target area	- the image of the field stop in object space. Also the area in the focal of the radiation thermometer which is sensitive to radiation.
Wien's law	- the product of the blackbody temperature and the wavelength corresponding to maximum radiance is a constant equal to 0.2898 cm K.

SECTION 2

DESCRIPTION OF THE PROBLEM

Work at the TFTF may sometimes be viewed as qualitative thermal testing with results showing a material specimen to be either satisfactory or unsatisfactory for the intended application. When thermal testing is an experimental step in materials development research, all parameters of the test become significant in the analysis of experimental results and should be determined and recorded quantitatively.

Surface temperatures of material specimens being tested at the TFTF were often not accurately known because of measurement difficulties, even though temperature is probably the most significant variable used in defining material properties. Contact probes for temperature measurements in many cases are not satisfactory for TFTF experiments because of both the interference they cause between source and specimen and the difficulty in maintaining surface contact under harsh test conditions. To circumvent the temperature measurement problems, thermocouples are frequently emplaced on the test specimen at locations other than on the heated surface. In some cases these substitute measurements are entirely adequate, while in others, temperatures measured in this fashion are quite irrelevant to physical changes which occur at the specimen surface.

The temperature measurement system developed under this project was designed to overcome, in so far as possible, the problems of operating a radiation pyrometer in the TFTF environment and to provide a continuous monitor of radiation from the surface throughout the test process even though a specimen may be tested to destruction.

2-1 ENVIRONMENTAL CONDITIONS AT THE TFTF.

Several somewhat unique environmental conditions exist at the TFTF which impact the use of a radiation pyrometer as a temperature monitoring instrument. Because radiation pyrometers are widely used in extremely harsh environments for monitoring various manufacturing and chemical processes, the TFTF environment is no threat to the instrument. However, correct interpretation of the pyrometer signals and accuracy of the temperature measurements becomes less certain because of some environmental factors present at the TFTF.

2-1.1 The Geometry.

Radiation pyrometers are designed to receive radiation from a region referred to as the target area on the hot object. An unobstructed optical path from the entire target area to the sensor is required for calibrated temperature measurements. At the TFTF it is not possible for the pyrometer to have an unobstructed field of view because of the small space between the test

specimen and radiation source. This difficulty is overcome by vignetting the instrumental field of view and making necessary sensitivity corrections.

2-1.2 The Radiation Environment.

Accurate temperature measurement by radiation pyrometry relies on properly detecting and interpreting the quantity and spectrum of radiation emitted by a hot target area. Interference from spurious radiation sources other than the target area will preclude accurate temperature measurements.

The thermal source at this test facility is an array of tungsten filaments operated at temperatures up to approximately 2800°K. Applying the Stefan-Boltzmann radiation law, these tungsten filaments radiate about a factor of 50 more energy per unit area than the test specimen target area when the specimen temperature is at the top of the pyrometer measurement range (~1173°K). At low specimen temperatures the tungsten lamps will radiate more than 10^5 times as much energy per unit area as the target.

Fused silica envelopes enclose the filaments, and a ¼-inch-thick quartz plate further isolates the test chamber from the tungsten radiation source. The transmittance of quartz and fused silica varies with composition, so precise values are almost never known, but the average thickness of quartz which separates the tungsten filament from the test chamber attenuates all radiation with wavelengths greater than 5μm by at least a factor of 10^7. The Model GP301 radiation pyrometer utilizes radiation in the wavelength band of 8 to 11.5μm only. Blocking filters in the pyrometer optical system have an attenuation factor of 10^6 or more for all wavelengths shorter than 5μm. This combination of quartz filtering in the thermal source and band pass filters in the pyrometer provides the necessary isolation to allow the radiation pyrometer to operate satisfactorily in the radiation flux of the tungsten filaments.

A more serious problem arises from background radiation emitted from the interior walls of the test chamber. It must be assumed that the chamber walls will absorb radiant energy at a rate as great as and in some cases much greater than the test specimen. Radiation reemitted by the test chamber walls would then equal or exceed that from the specimen and could interfere with accurate radiation pyrometer measurements. Appendix A addresses this problem and the correction procedure which allows temperature data to be extracted under some high background conditions.

2-1.3 The Experimental Facilities.

Ambient conditions existing at the TFTF provide a harsh environment in which to operate the radiation pyrometer but the problems are largely mitigated by support available at the facility. Significant local heating occurs during periods when the tungsten filaments are operating so a water-cooled jacket encloses all thermometer components which are located near the

test chamber. The large heat capacity of the metal water jacket will prevent short term changes in temperature of the enclosed thermometer and should provide all the temperature control necessary without actually circulating water in the jacket.

Controlled temperature water can be circulated in the jacket to maintain the thermometer at a specific temperature if desired.

When the water jacket cooling is used, precautions outlined in the manufacturer's literature should be heeded to avoid condensation from forming on optical components. A filtered air supply capable of delivering 4 cfm is required for purging the optical system to keep all components free of smoke and debris from the test specimen.

Data processing equipment used for the thermal test experiments can easily accommodate the added requirements of the radiation pyrometer for data storage and analysis.

2-1.4 The Test Specimens.

With the diversity of test specimens and test objectives encountered at the TFTF, it is predictable that situations will arise which cannot be fully satisfied by the capabilities of this prototype pyrometer system. At least two potential problems relating to use of the radiation pyrometer can be foreseen.

(a) When specimens having a high reflection coefficient are being tested, the background component, $(1-\bar{E})\ V(t)$, of the total pyrometer output, $\bar{E}\ V(T) + (1-\bar{E})\ V(t)$, is predicted in some cases to be much larger than the signal component, $\bar{E}\ V(T)$. If this occurs, accurate temperature measurements with the radiation pyrometer are not possible.

Further discussion of the radiation background problem and methods for amelioration of pyrometer data taken in high background environments is found in Appendix A and in Section 4.

(b) A second problem area for pyrometer temperature measurements results when a specimen is tested to destruction or to a point where there are significant physical changes in the surface which release smoke and debris into the test chamber. Unpredictable changes in emissivity which are expected to accompany changes in the specimen's surface condition can lead to extremely inaccurate pyrometer temperature measurements.

Material evolved from test specimens will also coat the walls of the test chamber creating emissivity changes which affect the radiation environment within the chamber, and therefore the pyrometer background

correction. Evolved material in the test chamber also presents a potential hazard to pyrometer operation if it reaches optical components. The resolution of this potential problem is discussed in Section 3-5.

2-2 USER SURVEY.

Design of the radiation pyrometer for use at the TFTF was based on input from three principal sources.

(a) The basic source of information on radiation pyrometry was engineers engaged in the design and production of commercial pyrometers. Assistance from this source made it possible to choose the best system components for reliability and functionality. This included the type of optical system, sensor, and signal processor.

(b) A survey of facility users was the second essential source of information for this pyrometer development work. Because the satisfaction of all possible noncontact temperature measurement needs of future users was a high priority objective of the project, information input from users of the TFTF was solicited through a telephone survey. The survey instrument was formulated both to determine the specific needs of current projects for front surface temperature measurements through specific questions on temperature ranges, time response, target area size and specimen properties, and to solicit comments and discussion useful in reaching a consensus on the desirable characteristics of a noncontact temperature measuring system.

(c) The third essential information source was the staff at the TFTF. They provided assistance and information for interfacing the pyrometer with the test facility and its support equipment and for meeting facility operational requirements.

Research personnel at the following companies were contacted and made contributions to the user survey results:

(1) McDonnell Aircraft Company
St. Louis, MO

(2) Boeing Military Airplane Company
Seattle, WA

(3) Northrop Corporation
Hawthorne, CA

(4) Aerojet Strategic Propulsion Company
Sacramento, CA

(5) Martin Marietta Corporation
Denver Aerospace
Denver, CO

(6) Raytheon Company
Wayland, MA

(7) Boeing Aerospace Company
Seattle, WA

(8) CAAP Company
Huntington, CT

(9) Vought Corporation
Dallas, TX

(10) General Dynamics, Convair
San Diego, CA

(11) McDonnell Douglas Astronautics Corporation
Huntington Beach, CA

(12) General Research Corporation
Santa Barbara, CA

(13) Martin Marietta Aerospace
New Orleans, LA

(14) Research Development Associates
Marina Del Rey, CA

(15) Southern Research Institute
Birmingham, AL

(16) Harold Rosenbaum Associates
Burlington, MA

SECTION 3

PYROMETER DEVELOPMENT

Radiation pyrometers, or radiation thermometers as they are frequently referred to, are now commonly used by industry for temperature control and monitoring. Most of these applications are highly specialized and commercially available equipment is often designed for one of these special applications. It could be very costly to adapt a highly specialized pyrometer to the needs of a research facility. This development task was undertaken, however, with the expectation that most of the technical and functional requirements could be met with a commercially available radiation pyrometer and that special features necessary for TFTF applications could be added through modifications to the selected instrument.

A study of available pyrometers was conducted to find the instrument most consistent with the requirements identified by the user survey. Pyrometers were evaluated on the basis of five different factors which are discussed in Sections 3-1 through 3-5. Acceptable specifications in all of the five selection areas were flexible within limits. Most rigid was the spectral response requirement. Because of the extremely high radiation flux from the tungsten lamps, it has required that the pyrometer operate at wavelengths greater than 8μm and that the blocking factor for all wavelengths shorter than 5μm be 10^6 or greater.

A Land Model GP301 Infrared Pyrometer with modifications to the response time and field of view was selected as meeting all identified technical requirements for the least cost in terms of both dollars and procurement time.

3-1 TEMPERATURE SPAN.

All users surveyed reported that the highest temperature they would need to measure in current work was 1500°F (815°C). One reported that a peak temperature of 2000°F (1093°C) would be reached in the near future. All respondents agreed that it would be very desirable for the radiation thermometer to be useable down to about 100°C. It was further agreed that the instrument should cover this entire range of temperatures without a change of scale.

The Land Model GP301 Pyrometer covers the range from 0 to 900°C without a scale change. The measurement accuracy of the unmodified pyrometer is given as ±0.25% + 1°C. Modifications to the instrument's response time, which are discussed in Section 3-2, greatly increased the noise level of the pyrometer and therefore the effective measurement errors.

The temperature span of this model is more than adequate for all current work but does not satisfy the future requirement of 2000°F foreseen by

one researcher. If a real need for measuring higher peak temperature develops, the thermometer unit of this instrument can be replaced, at a very reasonable cost, by one which extends up to 2700°F but which will not respond to temperatures lower than approximately 300°F.

3-2 TIME RESPONSE.

Response time of the Model GP301 Pyrometer marketed by Land Instruments Inc. is specified to be 1 second to 98% of final output voltage. This instrument uses a pyroelectric sensor with characteristic response time of a few milliseconds. The relatively slow response of the instrument results from a long signal integration time necessary for good measurement precision; fast response is not needed for most industrial applications.

The survey showed that most users thought a response time of 0.1 second would meet current needs but some felt a response time of 0.025 second was needed. The manufacturer agreed first to modify the Model GP301 to have a 0.1 second response time and then later to meet our request for a 0.025 second response time. A signal rise time of 0.025 second to 98% of the final value is indeed an excellent response but it was costly in terms of signal noise. The measured rms noise level on the pyrometer signal after the response time modification is shown in Figure 3-1. In most applications this higher noise will not be a problem. If it should be, however, it can be reduced by increasing the signal integration but a slower response time will result.

3-3 SPECTRAL RESPONSE.

The measurement of radiation from a relatively cool surface, 200°C or less, in the vicinity of 2500°C tungsten filaments is a formidable undertaking. It is only possible because there are thick quartz filters between the hot filaments and the test chamber. Quartz is an effective absorber of all wavelengths greater than 5μm. For a blackbody spectrum at 2500°C, approximately 3.7% of the total energy radiated from the filaments has wavelengths longer than 5μm; the quartz window attenuates this portion of the spectrum by a factor of 10^7 so the test chamber is quite "dark" in this wavelength region. An infrared radiation pyrometer which is sensitive to wavelengths between 8 and 11.5μm was selected to take advantage of the relatively low radiation environment beyond the quartz cut-off. The use of an instrument which is insensitive to wavelengths shorter than 8 μm is absolutely essential for this application.

The short wave blocking filters in the Model GP301 should provide attenuation of 10^7 or greater for all wavelengths shorter than approximately 6μm. Spectral specifications of the Model GP301 Pyrometer meet the TFTF requirements.

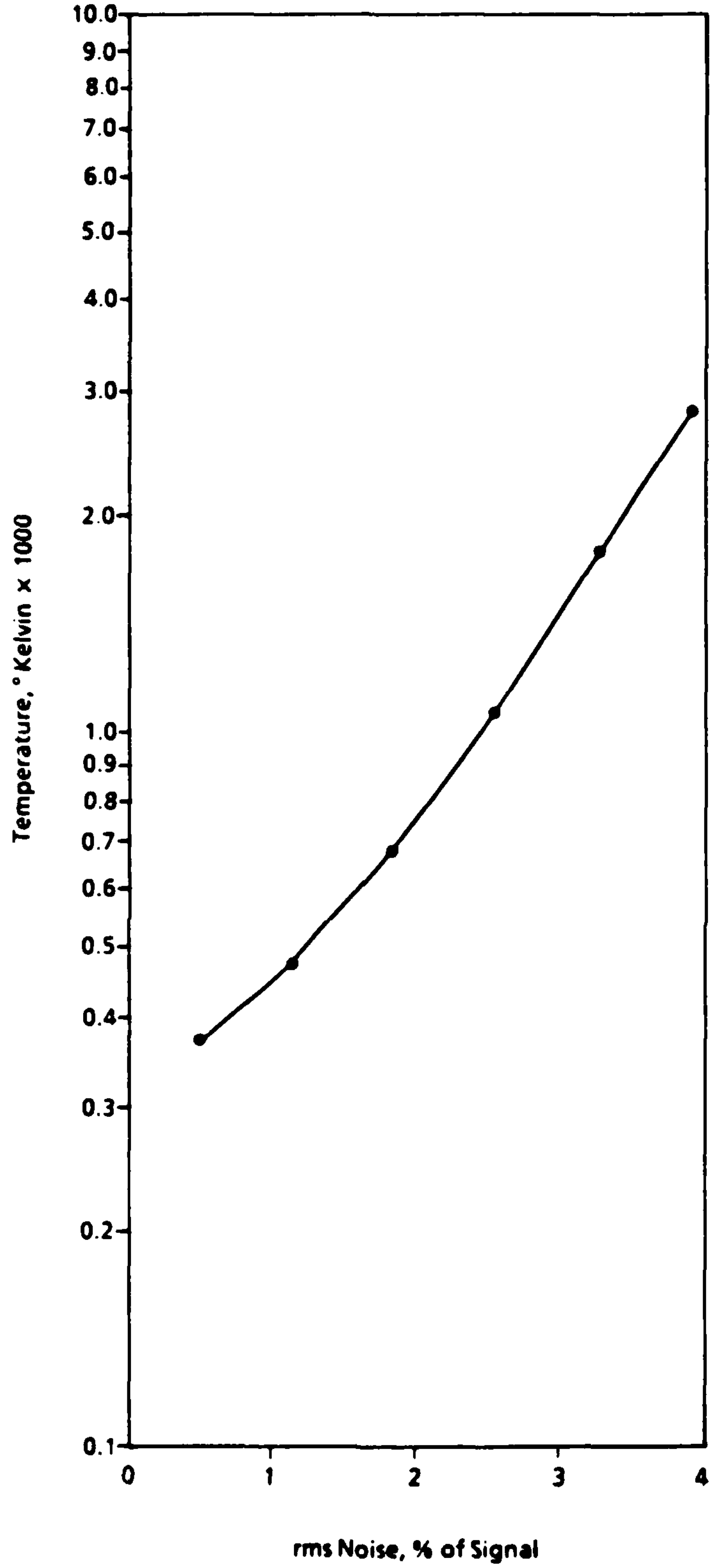

Figure 3-1. Measured rms noise as percent of signal versus source temperature for the Land Pyrometer Model GP301-Z1153.

3-4 OPTICAL VIEWING ANGLE AND FIELD OF VIEW.

The TFTF test chamber is designed to deposit the maximum radiant energy on the test specimen. This requires a thermal source which subtends a large solid angle at the test specimen and very close source-specimen spacing. This geometry obscures all optical paths which are best suited for making pyrometer temperature measurements. It is necessary to place the optical system and sensors either above or below the test chamber at a very large angle to the specimen surface normal. Figure 3-2 illustrates the relative locations of test chamber, specimen, and pyrometer line of sight. The test chamber geometry determines the viewing angle and focal distance which in turn determines the most desirable optical parameters.

The only possible line of sight to the front surface of the specimen plate allows the thermometer to be no closer than 5 inches (127 mm) from the specimen so a lens system of 125 mm (4.92 inches) focal length was chosen. Because a thermometer capable of measuring temperatures down to 0°C was selected, use of a high speed lens which has an acceptance angle of 1/30 radian is required. This together with the focal distance determines that the pyrometer target will be a 5-mm (0.197-inch) diameter circle at 125 mm (4.92 inches) from the principal plane of the lens system.

The Land lens systems have an aperture stop of 22 mm (0.87 inch) which is considerably larger than the opening through which the line-of-sight (LOS) must pass. A modification to the optical system was made to systematically vignette the field of view by a water-cooled radiation channel which accommodates the pyrometer optical system to the test chamber geometry with no adverse effects except to reduce the system sensitivity by a constant fixed factor. Details of the water-cooled radiation channel and its interface to the thermometer water jacket are shown in Figure 3-3.

The sensitivity reduction caused by reducing the aperture stop is estimated to increase the minimum detectable temperature from 0°C to approximately 20°C. Anticipation of this increase in minimum detectable temperature was a factor in not choosing the pyrometer model with a minimum temperature of 100°C.

The optical system of the selected pyrometer was satisfactory in all respects except for aperture size.

3-5 COOLING, PURGING AND SHOCK MOUNTING.

The Model GP301 Pyrometer was designed for industrial applications. To function in industrial environments, the options of water cooling and air purging and cooling are available. These options are included on the instrument supplied to the TFTF. Water cooling of the thermometer at the TFTF may never be required but the cooling jacket provides a more stable temperature environment. Air purge of the optical system and LOS channel with approximately 2 cfm of cool, dry, filtered air is strongly recommended to prevent accumulations of foreign materials on the optical surfaces and LOS channel walls.

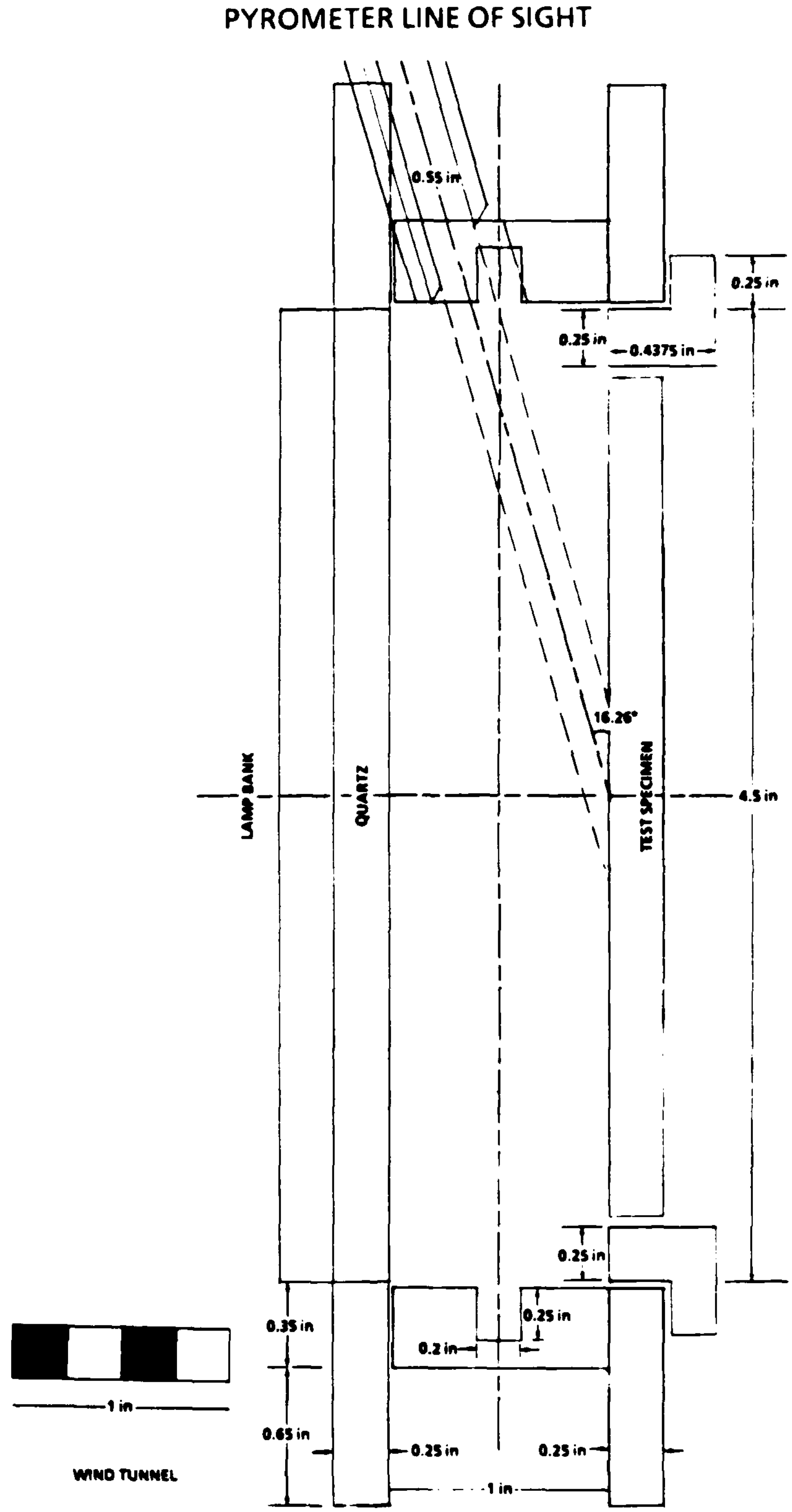

Figure 3-2. Vertical section of the test chamber at the Tri-Services Thermal Flash Test Facility.

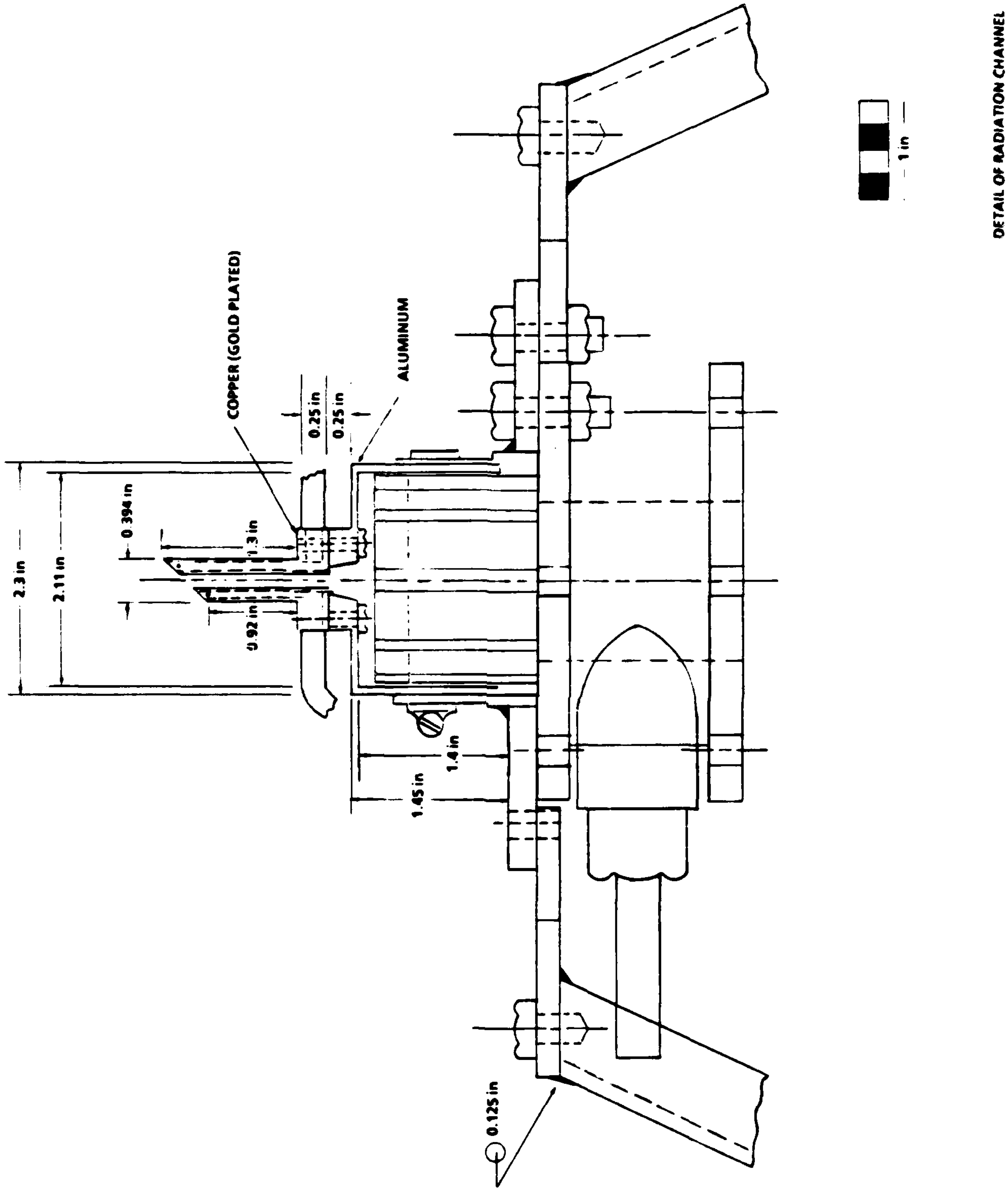

Figure 3-3. Water-cooled radiation channel on the Land Model O/N/PA radiation thermometer jacket.

A small thickness of soft material should be maintained between the thermometer housing and the test chamber walls to isolate the thermometer from vibrations of the test chamber blowers.

3-6 THE SIGNAL PROCESSOR.

A Land System 3 digital signal processor was selected for use with the GP301 thermometer. Because the System 3 processor does not provide easily adjustable emissivity corrections, these corrections will be performed on the facility computer. All necessary adjustments have been performed so normally the processor unit will not need further adjustment before a periodic system calibration is performed. This signal processor provides for three different voltage or current signal output modes which may be selected for the best interface with data recording equipment. Also, voltage outputs which are directly proportional to either degrees Centigrade or Fahrenheit are available.

SECTION 4

RESULTS AND CONCLUSIONS

A comprehensive survey of researchers representing government contractors who use the Tri-Services Thermal Flash Test Facility (TFTF) for materials development projects was conducted to determine what specific capabilities for front surface, noncontact temperature measurements were needed at the facility.

From the results of this survey, specifications for a temperature measuring instrument meeting the user perceived needs were developed. On the basis of these specifications, a Land Model GP301 long wavelength infrared radiation thermometer and System 3 signal processor produced by Land Pyrometer Ltd., Dronfield, England, were selected as the basic instrument which most nearly met the TFTF specifications.

The manufacturer agreed to modify the pyrometer to change its response time from 1 second to 0.025 second. The modification was performed and the instrument delivered with a certification that the response time specification was satisfied. The pyrometer output noise level concomitant with the shorter time constant is shown in Figure 3-1. This noise component is equivalent to a measurement uncertainty of ±1.6% or ±15°C (250°F) at the maximum temperature of 900°C (1600°F).

Modification of the aperture stop to facilitate interfacing the pyrometer to the TFTF test chamber resulted in an increase in the minimum detectable temperature to approximately 20°C.

The following specifications apply to the Model GP301-Z1153 Pyrometer developed for use at the TFTF.

Working range	20 to 900°C
Uncertainty	$\leq$ ±1.6% of temperature (°C)
Output	10 Volts maximum
Output load	230 ohms
Lens material	Zinc sulphide
Response time	0.025 second to 98%
Detector	Pyroelectric
Spectral response	8 to 11.5μm
Operating temperature range	10 to 50°C

Some preliminary data taken at the TFTF with a high emissivity specimen plate shows that the pyrometer functions well in the test chamber environment, giving apparent front surface temperature values which correlate well with back surface temperatures measured concurrently with a thermocouple.

The experience accumulated with this instrument, although still quite limited, indicates that additional instrumental development for pyrometry is not needed at this time.

Data taken with a low emissivity specimen confirm the necessity of system calibration and background determination procedures discussed in Appendix A.

The precise capabilities and limitations of this instrument for front surface temperature measurements will only be known after calibration procedures are fully implemented and techniques for temperature and emissivity monitoring at the TFTF are further developed.

Some photographs of the pyrometer and its support equipment are presented in Figures 4-1 through 4-3.

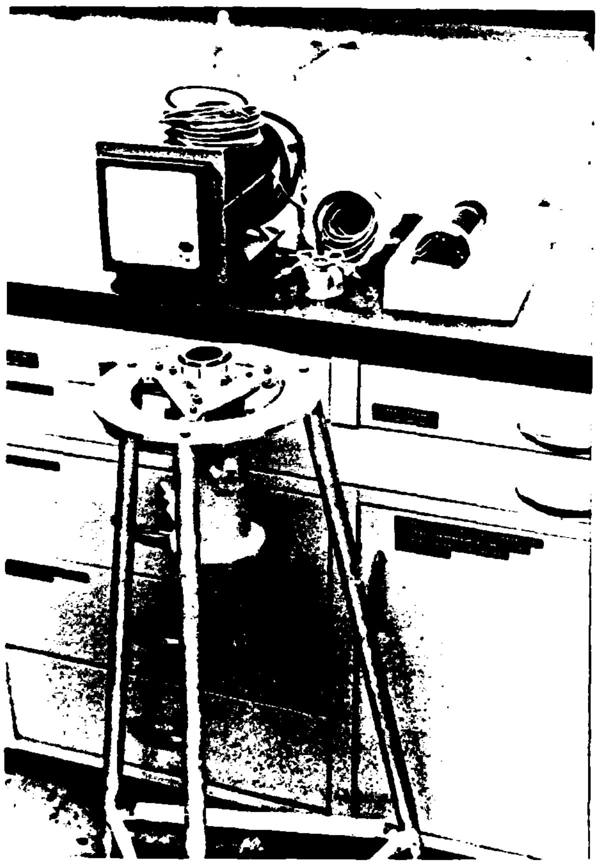

Figure 4-1. Pyrometer and its support equipment.

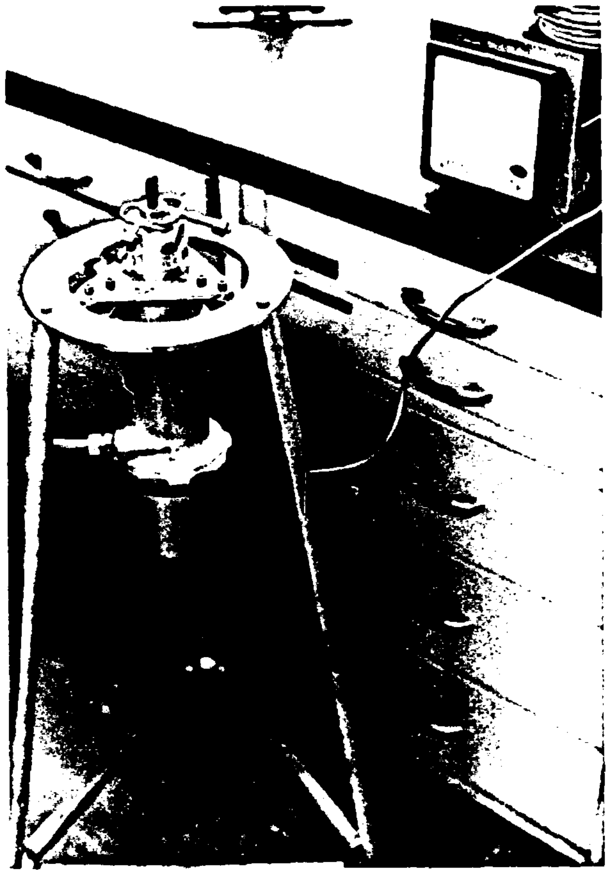

Figure 4-2. Pyrometer support equipment.

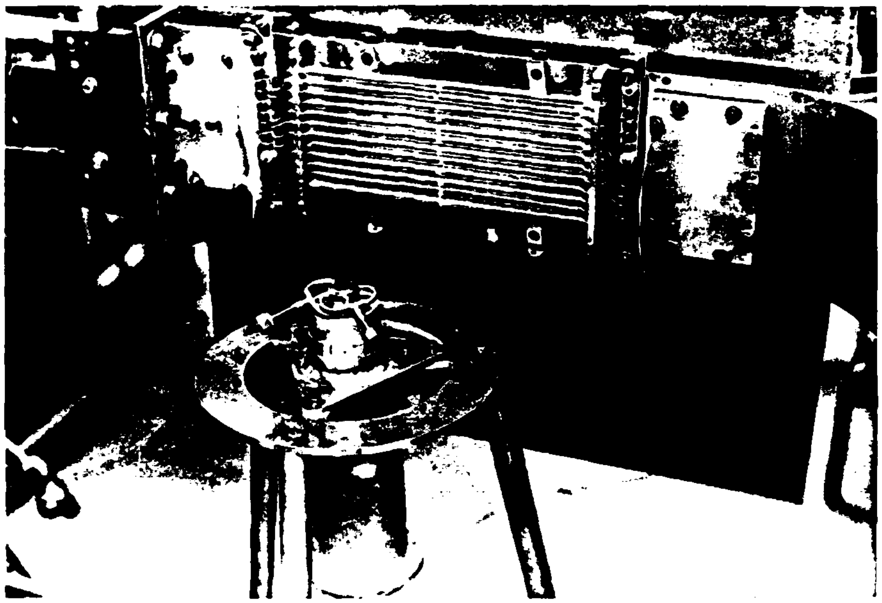

Figure 4-3. Pyrometer support equipment and test chamber.

APPENDIX A

FRONT SURFACE PYROMETER CALIBRATION PROCEDURE

A-1 INTRODUCTION.

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Radiation thermometers determine a material's surface temperature by monitoring electromagnetic radiation emitted from that surface. The infrared thermometer was designed to measure front surface temperature at the Tri-Services Thermal Flash Test Facility (TFTF) by monitoring radiation emitted from a test specimen while it is in the test chamber.

The pyrometer supplied to the TFTF under this contract is a relatively rugged and reliable instrument. It is prudent, however, to periodically reconfirm that the instrument is functioning properly. The three tests outlined in Subsection A-2 below should be performed if the proper functioning of the instrument is in question for any reason or after use for a period of one or two years.

An accurate relationship between the signal produced by radiant energy incident on the instrument's sensor system and the temperature of the emitting surface must be established through sensitivity calibration. The calibration procedure developed for use at the TFTF is divided into three separate parts, each part fulfills a separate and distinct need in the process of establishing and maintaining the infrared thermometer as an accurate and reliable tool for front surface temperature determination.

Part I is a blackbody calibration and is designed to confirm the proper operation of the thermometer and signal processor. For this portion of the calibration a blackbody source is required. The pyrometer output voltage and the corresponding blackbody temperature, measured by a standardized thermocouple, are recorded to form a calibration table covering the full temperature span of the pyrometer.

Part II of the calibration procedure will develop a calibration table which relates the radiation pyrometer output signal to a secondary temperature standard when the pyrometer is operated in the test chamber configuration. This calibration will differ from the blackbody calibration in that the instrumental field of view will not be totally filled by the test object, the viewing angle will be approximately 75 degrees from the surface normal and the effect of large angle emissivity from metal surfaces will be a factor.

Part III is a procedure for determining some environmental background effects of the test chamber on the temperature measuring pyrometer.

Results of this procedure will be used to determine the limits of validity for measurements made in high background environments and for making corrections to measured temperatures when possible.

A-2 PRELIMINARY/PERIODIC TESTS.

The following tests should be performed at some time during the period when the infrared thermometer is being integrated into the test facility. They should also perhaps be repeated at approximately one-year intervals or after the instrument has been accidentally damaged in any way.

A-2.1 Stability Test.

Record the output signal from the infrared thermometer while it is reading the temperature of a stable thermal source for a continuous period of 24 hours. It is best to use a blackbody source for this test and record both the blackbody temperature and the thermometer output.

A-2.2 Optical System Test.

Use a circular, 5-mm (0.197-inch) diameter mask to test the thermometer output as a function of the field stop image size and position around the intersection of the instrument's focal plane and optic axis. This will confirm the mechanical integrity of the sensor and optical components.

A-2.3 Ambient Temperature.

This test is intended to confirm the independence of the thermometer sensitivity from ambient temperature variations. The test is performed by setting the thermometer to read the temperature of a stable blackbody source. The ambient temperature of the thermometer is then varied over a range of about 30°F by flowing water from a temperature controlled water bath through the water pocket. Care should be exercised to not operate the thermometer colder than the dew point or hotter than the recommended temperature. Between 70°F and 100°F are suggested. Because several hours are required to establish temperature equilibrium when the thermometer temperature is changed, this test is best combined with the stability test.

A-3 CALIBRATION PROCEDURES.

A-3.1 Part I: Blackbody Calibration.

Items of equipment used for Part I of the pyrometer calibration are

(a) a blackbody source having an aperture of 2 inches (50.8 mm),
(b) a thermocouple which qualifies as a secondary temperature standard
to monitor the blackbody temperature, and
(c) a voltage measuring device accurate to 1 mV over the range of 1 to
2,000 mV.

This calibration procedure is relatively easy to perform if the limits of accuracy are not too strict. The desired calibration accuracy should first be selected. Uncertainties in emissivities and effects of background radiation from the test chamber walls will be the two principal contributors to temperature measurement errors. Pyrometer calibration errors, the third contribution, can easily be made the smallest of the three which is all that is necessary because they will combine statistically to give the total error. For this reason a calibration accuracy for the instrument of ±10°K should be adequate.

Sensitivity calibration is often referred to as an experimental determination of the instrumental scale shape which is the relationship between the thermometer output signal and the blackbody temperature being monitored. The TFTF pyrometer is comprised of the infrared thermometer and a signal processor which is designed to convert the characteristic thermometer scale shape curve shown in Figure A-1 to a linear relationship between pyrometer signal and blackbody temperature with a slope of $dV/dT = 1$ mV/°F.

A scale shape table applicable to the Land Thermometer Model GP30 is attached as Table A-1. The Land System 3 Signal Processor converts the thermometer scale shape function to a linear function of blackbody source temperature. The following blackbody calibration steps are for the determination of a scale shape table for the thermometer and signal processor combination. Ideally, it should show a linear relationship between source temperature and processor output voltage, but in practice the blackbody calibration will show small deviations from the ideal relationship.

Step 1. The infrared thermometer must be rigidly mounted in a position relative to a blackbody source such that the thermometer optic axis is normal to the source plane and the target area is completely filled by unobstructed radiation from a blackbody source. The target area of this instrument is a 5-mm (0.197 inch) diameter circle at a distance of 125 mm (4.92 inches) from the objective lens. Distance from source to sensor is not important if the target or its projected area in the 1/30 field of view angle is completely filled by the source.

Step 2. The blackbody temperature must be monitored by a thermocouple which qualifies as a secondary temperature standard. Preferably the

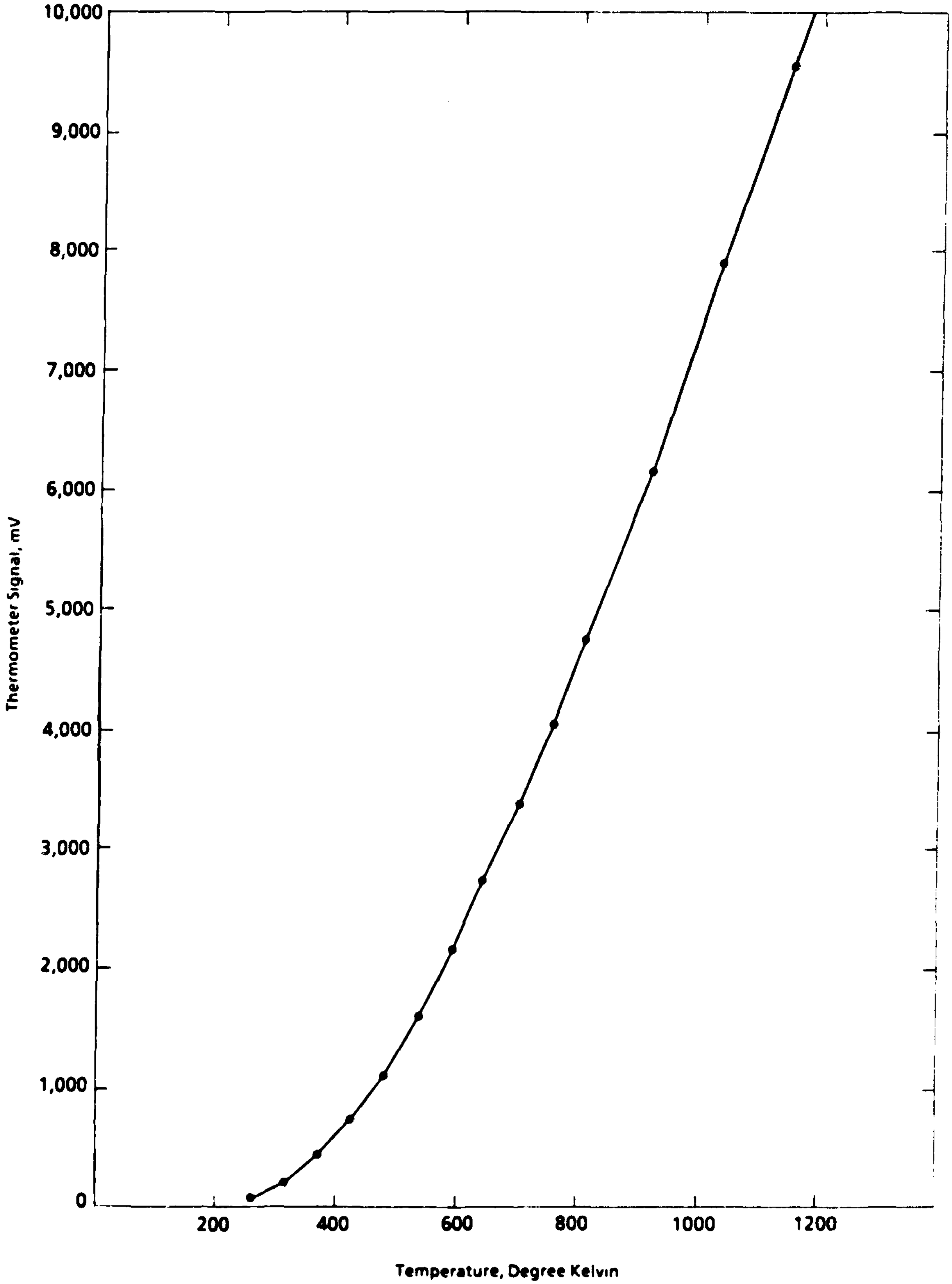

Figure A-1. Measured scale shape for Land Thermometer Type GP30.

Table A-1. Output from the thermometer when the thermometer field of view is completely filled and the emissivity of the target is unity.

Note: Master scale shape for GP3, thermometer type GP30, temperature range 0 to 1,650°F.

°F	0	10	20	30	40	50	60	70	80	90
					mV					
0	72.07	81.50	91.70	102.7	114.5	127.2	140.7	155.2	170.4	186.6
100	203.7	221.7	240.6	260.5	281.3	303.0	325.6	349.2	373.7	399.1
200	425.5	452.8	481.0	510.2	540.2	571.1	603.0	635.7	669.3	703.8
300	739.1	775.3	812.4	850.3	889.0	928.5	968.8	1,010	1,052	1,095
400	1,138	1,182	1,227	1,273	1,319	1,366	1,414	1,463	1,512	1,562
500	1,612	1,663	1,715	1,768	1,821	1,874	1,929	1,984	2,039	2,095
600	2,152	2,209	2,266	2,325	2,383	2,443	2,502	2,563	2,623	2,684
700	2,746	2,808	2,871	2,934	2,998	3,062	3,126	3,191	3,256	3,322
800	3,388	3,454	3,521	3,588	3,656	3,724	3,792	3,861	3,930	3,999
900	4,069	4,139	4,210	4,281	4,352	4,423	4,495	4,567	4,639	4,712
1,000	4,784	4,858	4,931	5,005	5,079	5,153	5,228	5,303	5,378	5,453
1,100	5,529	5,604	5,680	5,757	5,833	5,910	5,987	6,064	6,142	6,219
1,200	6,297	6,375	6,454	6,532	6,611	6,690	6,769	6,848	6,928	7,008
1,300	7,087	7,168	7,248	7,328	7,409	7,490	7,571	7,652	7,733	7,814
1,400	7,896	7,978	8,060	8,142	8,224	8,306	8,389	8,472	8,554	8,637
1,500	8,720	8,804	8,887	8,971	9,054	9,138	9,222	9,306	9,390	9,475
1,600	9,559	9,644	9,728	9,813	9,898	9,983				

blackbody temperature should be monitored by two thermocouples which can be calibrated at a standards laboratory. Traceability of the TFTF instrument calibration to a thermal standards laboratory is certainly not necessary; but, should a client request it, it would be easily achievable if the thermocouples are properly used.

Step 3. With the infrared thermometer positioned so the blackbody source completely fills its field of view, a table of source temperatures versus pyrometer output voltage is recorded. Readings should be taken at appropriate intervals over the entire range in which the pyrometer will be used.

This calibration table defining the relationship between source temperature and pyrometer output should be entered into the facility computer for easy availability and also converted to a calibration curve for user convenience.

Step 4. Two additional tables and/or curves will be derived from the calibration table. One is a table of first moments or slopes of the calibration curve at each temperature. This curve represents the function dV/dT which is the change in output voltage observed for a unit change in temperature. This function is needed to convert measurement voltage errors into temperature errors. The other derived function is an expression of the effective wavelength (λ) for the thermometer as a function of temperature. Analytically it can be expressed as $\lambda = CVdT/T^2dV$, where C is a constant, V is pyrometer output voltage and T is the calibration source temperature.

This procedure generates a calibration table which can be used to correct for the instrument response and to judge if it is functioning properly. The two derived functions are needed to determine the magnitude of temperature errors for known signal errors and to correct for emissivity.

These tables will normally be stored and used only through the facility computer although it is desirable to have a hard copy of the curves available for users.

A-3.2 Part II: Facility Calibration.

This procedure requires the use of the pyrometer including the water-cooled radiation channel, one or more graybody thermal sources with thermocouple monitors and hardware for positioning the thermometer relative to the thermal source. Graybody sources have an emission spectrum shape similar to a blackbody source but reduced in amplitude by an emissivity value which is less than one (1).

Procedures followed in Part II of the calibration process are basically the same as those in Part I. The objective of Part II is to experimentally determine a scale shape table for the system of which the infrared pyrometer calibrated in Part I is one component. Proper operation of the pyrometer was confirmed by the Part I calibration so it is now possible to proceed with the assurance that the scale shape measured in Part II results from system parameters and not from a malfunction in active pyrometer components.

Graybody thermal sources will be prepared of both metal and dielectric material with surface monitoring thermocouples implanted as near as possible to one surface. The sources will be heated from the back surface by a controllable heating element. Emissivity and surface properties of these graybody sources should be preselected to cover a range of conditions considered most useful to facility users. The thermometer will be positioned at an angle and distance which simulates actual test chamber conditions.

Step 1. The thermometer with its water-cooled radiation channel in place must be rigidly supported in a position relative to the thermal source which simulates its test chamber configuration. The positioning mechanism should provide for adjustability in both angle and distance between the thermometer and thermal source so that the actual test configuration can be reproduced exactly.

Step 2. Signals from two or more thermocouples embedded in the front surface of the graybody source are recorded to monitor the front surface temperature as heat is applied to the back surface. These thermocouples should qualify as a transfer standard which can be calibrated at a standards laboratory if desired. They will be positioned across the surface to indicate temperature gradients in addition to the average temperature of the surface [illegible]ating toward the pyrometer.

Step 3. A calibration table or scale shape function of pyrometer output versus graybody temperature is experimentally determined by simultaneously recording the pyrometer and thermocouple signals. Readings of pyrometer signal versus temperature are taken at appropriate intervals but the total temperature range of the pyrometer will often not be covered because of limitations of the graybody material.

Several factors contribute to this calibration which were not present in Part I. Some, such as the transmission of the radiation channel, should not change the scale shape but others, such as the change of emissivity with surface temperature and angle, probably will. As a result, derivation of dT/dV and λ(effective) will be repeated for the new scale shape and will be applied to measurement errors and source emissivities to determine the effect of these system factors on measurement errors.

Results of this calibration procedure will also be stored in the facility computers and used by the data analysis software.

A-3.3 Part III: Background Signal Determination.

This procedure makes use of the front surface pyrometer in its operational configuration and some simulated test specimens which span a wide range of emissivities and which can be instrumented with thermocouples implanted as near as possible to the front surface. Several thermocouples will also be positioned to monitor test chamber wall temperatures.

The tungsten lampbank will provide the thermal source to experimentally determine a table of pyrometer output signal versus temperature of the test specimen surface and temperature at several points on the interior wall of the test chamber.

The radiation pyrometer will produce a total signal which is the sum of the signal emitted by the specimen given by $\bar{E}$ V(T) and the signal emitted by the test chamber walls and reflected into the pyrometer field of view at the specimen surface. The reflected signal can be represented by $(1-\bar{E})\ V(t)$ so the sum of direct and reflected signals is $\bar{E}\ V(T) + (1-\bar{E})\ V(t)$. In this expression, $\bar{E}$ is the effective test specimen emissivity over the 8 to 11.5-μm band, V(T) and V(t) are the signals which would result from blackbody sources of temperatures T and t respectively.

The term $(1-\bar{E})\ V(t)$ represents the background signal due to the test chamber environment. There will be a functional relationship between $(1-\bar{E})\ V(t)$ and the specimen temperature which also depends on several other parameters such as specimen emissivity, how the shutter and blowers are used, and so forth. Tables of pyrometer signal versus specimen temperature for various values of the principal parameter will be determined experimentally. These tables can then be used to deduce effective environmental temperature, t, and to to determine the corrections, $(1-\bar{E})\ V(t)$, to be applied to the pyrometer measurements.

APPENDIX B

PROCEDURE FOR CORRECTING INDICATED TEMPERATURE BASED ON MATERIAL EMISSIVITY

B-1 INTRODUCTION.

Emissive power or emissivity, a fundamental property of material surfaces, is defined as the energy radiated from unit area of a surface in unit time for unit difference of temperature between the surface and the surrounding environment. Tabulated values of emissive power in the cgs system of units are in ergs per second per square centimeter radiated from a surface at 1 degree Kelvin in an absolute zero environment.

The words "emissivity" and "emissive power" are used interchangeably in physics, but in radiation pyrometry emissivity (E) is always used to mean not emissive power but the ratio of emissive power of an object in question to the emissive power of an ideal blackbody.

Emissive power as defined above includes all wavelengths of radiation and emission at all angles from the surface. Emissivity as used in radiation pyrometry is generally restricted to specific wavelengths, and is referred to as spectral emissivity, and to emission at specific angles to the surface normal. Planck's radiation formula, $J(\lambda,T) = c_1 \lambda^{-5} [\exp (c_2/\lambda T)-1]^{-1}$, is the analytical expression of emissive power for a 2π solid angle at the wavelength, λ, and temperature, T. In Planck's formula c_1 and c_2 are derived physical constants having values of 3.74×10^{-20} watt·cm^2 and 1.439 cm·°K respectively.

Temperature measurements at the Tri-Services Thermal Flash Test Facility (TFTF) using the infrared thermometer Model GP301-Z1153 are dependent upon mean emissivity ($\bar{E}$) over the spectral range of 8 to 11.5μm. Mean emissivity is defined as the spectral emissivity weighted by the Planck function and instrumental responses. Analytically,

$$\bar{E} = \frac{\int_0^\infty d\lambda\, E_\lambda J(\lambda,T) I(\lambda)}{\int_0^\infty d\lambda\, J(\lambda,T) I(\lambda)} \qquad (1)$$

where $I(\lambda)$ is the total response of the pyrometer including sensor, optics, and spectral filters, $J(\lambda,T)$ is the Planck function and E_λ is the spectral emissivity defined as the ratio of the test object emissive power to blackbody emissive power at the wavelength, λ. Land Instruments Inc. has assembled a table of mean emissivities appropriate to the GP3 series infrared thermometers

which is reproduced as Table B-1 in this report. For materials listed in existing tables and having appropriate surface properties, tabulated values of emissivity are often good enough for converting apparent temperatures to true temperatures.

B-2 EMISSIVITY CORRECTIONS.

Corrections based on material emissivity are always necessary to convert the apparent temperature measured by a radiation pyrometer, to the true temperature. These corrections are based on the definition of spectral emissivity which is given as the ratio of radiation energy emitted by a surface in a given wavelength interval to the radiation energy emitted by a blackbody in the same wavelength interval and at the same temperature.

The radiation pyrometer Model CP 301 incorporates a System 3 signal processor which automatically converts the radiation energy received to a corresponding apparent temperature. The instrument is calibrated such that this apparent temperature is the true temperature if the source is a blackbody, i.e., $E = 1$, and subtends the full field of view. Provision is also made for the signal processor to correct for source emissivities less than one and again compute a true temperature for the radiation source. Corrections for source emissivity by the System 3 signal processor require internal adjustments to the instrument so for TFTF activities which frequently involve emissivity changes, true temperatures should be calculated on the facility computer, not the signal processor.

The conversion of a measured apparent temperature to true temperature depends on converting the measured radiation signal to an equivalent blackbody signal. Environmental background radiation arriving at the pyrometer by reflection from the specimen surface complicates the problems of emissivity correction. This background radiation adds to radiation emitted by the monitored surface so the total pyrometer output is given by $\bar{E}\,V(T) + R\,V(t)$, where the surface reflectivity (R) is defined as the ratio of "radiant energy reflected from the surface" to the "radiant energy incident on the surface" $V(T)$ and $V(t)$ are the pyrometer signals from blackbody sources of temperature, T, and t respectively. Fundamental physical relationships result in the sum of the ratios for emissivity and reflectivity at an opaque surface being equal to one (1), so $R + \bar{E} = 1$. It is thus possible to write the pyrometer signal as $\bar{E}\,V(T) + (1-\bar{E})\,V(t)$. For the general case the measured temperature is a function of two unknowns, T and t and it is not possible to determine the values of both the test specimen temperature, T, and the background temperature, t, from one measurement.

To simplify the problem, consider radiation pyrometer temperature measurements in the following three different situations.

(a) The environmental temperature, t, is much lower than the specimen temperature, T, so $t \ll T$ and $V(t) \ll V(T)$. Then the background term, $V(t)$, can be neglected so $\bar{E}\,V(T) + (1-\bar{E})\,V(t) \sim \bar{E}\,V(T)$ and the approximate

true temperature is found by correcting the apparent temperature for an emissivity $\bar{E}$.

A similar approximation may be applied if $\bar{E} \sim 1$ so $(1-\bar{E})$ is very small and the background temperature, t, is comparable to or smaller than the specimen temperature, T. In this case also the background term can be neglected and because $\bar{E}$ is almost equal to 1, only a small emissivity correction is required. In these situations radiation pyrometry is an excellent method of temperature measurement.

(b) A second situation in which radiation pyrometry is often used is to measure the temperature of a specimen in an oven at temperature equilibrium. In this case,

$$T = t$$
and
$$\bar{E}\ V(T) + (1-\bar{E})\ V(t) = \bar{E}\ V(T) + (1-\bar{E})\ V(T) = V(T), \tag{2}$$

so the common specimen and background temperatures are independent of emissivity and can be determined as if they were blackbody radiators without emissivity correction. This equilibrium condition does not exist in the TFTF test chamber.

(c) The third situation covers those cases where a hot surface is in a hot environment but temperature equilibrium does not exist. Then, $T \neq t$, the pyrometer output is $\bar{E}\ V(T) + (\bar{E}-1)\ V(t)$ and the two different temperatures cannot be uniquely determined. This is the situation which normally exists in material tests at the TFTF.

The problem is analagous to problems encountered in many flux measurements in which high background signals prevent accurate results. The most common approach to dealing with this problem is to modify the environment to reduce the background. At the TFTF environmental conditions are largely determined by test requirements, therefore they cannot generally be changed to reduce background.

The best remaining approach to solving a background problem is by making simultaneous background measurements and using them to correct the measurements which include signal plus background. This is a possible approach at the TFTF but it does require considerable additional hardware on and around the test chamber.

Another approach to the problem is to make background determinations for the test chamber environment before test data are taken. Prior background measurements and knowledge of the test specimen emissivity could then be used to make background corrections to test data. The environment calibration tables produced in Step 3 of the calibration procedure are designed to give background signals required for this correction.

The pyrometer signal is then $\bar{E}\ V(T) + (1-\bar{E})\ V(t)$ in which $\bar{E}$ is known or determined and $V(t)$ is found in the environmental calibration tables for similar test parameters. Then, $(1-\bar{E})\ V(t)$ can be subtracted leaving $\bar{E}\ V(T)$ from which the apparent temperature is found and corrected to true temperature. The true temperatures thus derived do tend to have larger uncertainties.

B-3 EMISSIVITY DETERMINATIONS.

Front surface temperature measurements with a radiation pyrometer, as performed at the TFTF, can only produce apparent temperatures and knowledge of the source emissivity is necessary for the conversion of apparent temperature to true temperature. There are extensive tabulations of emissivities but experience has shown that tabulated values for emissivity are seldom applicable to one's specific need in radiation pyrometry.

Emissivity is often thought of as a property of materials which is relatively independent of other factors. In fact, emissivity varies with the physical properties of the emitting surface, the angle of view, the radiated wavelength and the temperature of the surface in addition to the emitting material.

With so many parameters tabulated emissivity values are almost never completely applicable to the situations in which they are applied. The Land Thermometer Model GP301-Z1153 responds to radiation in the wavelength region of 8 to 11.5µm. To correctly convert measured temperature from this instrument to true temperature the mean emissivity over this specific wavelength band and at a viewing angle of ~75° from the surface normal must be known. Land Instruments, Inc. has provided a table of emissivities applicable to the 8 to 11.5µm wavelength band included as Table B-1 in this report. Even these values must be used with caution because they are not completely valid for data taken at large viewing angles.

The problems with emissivity have no one good solution. The multistep procedures described here should, in most cases, enable the TFTF users to extract the needed front-surface temperature data from the radiation pyrometer without devoting an undue effort to emissivity determinations.

Step 1. Selecting the emissivity accuracy required.

In dealing with the problem, it is first necessary to determine the accuracy with which emissivity must be known to meet the need of each specific experiment. Some experiments may require only ratios of temperatures, or relative temperatures. In these cases, it is not necessary to know emissivities.

When true temperatures are required, the errors introduced by emissivity corrections need not be appreciably smaller than errors

from other sources or the allowable experimental error which is even larger. Emissivity errors translate directly into pyrometer signal errors which can be converted to true temperature errors. The relationship between emissivity and temperature error is found from the dV/dT table which was derived from the calibration scale shape. Thus, when allowable temperature uncertainty is selected for a specific experiment, the accuracy required of emissivity can be deduced.

Step 2. Using tabulated values of emissivity.

There is a large quantity of tabulated data on material emissivities. Because of the many parameters affecting emissivity, these tabulated values are never completely applicable to a specific experiment. For tests of newly developed materials, one must recognize that no data exists and emissivity measurements are required. For all common materials, emissivities have been measured usually at several temperatures and two different surface conditions. Most measurements were designed to integrate over a rather wide and often poorly defined wavelength region and to integrate either 2π viewing angles or a small solid angle nearly normal to the surface. In order to use tabulated emissivity values as input to quantitative measurements, it is necessary to know probable errors on this value when they are extrapolated to the wavelength band and viewing angle used at the TFTF. The material being tested, surface condition and temperature may also differ from those for which the emissivity was measured.

In order to be able to extrapolate tabulated values of emissivity to the parametric conditions of specific TFTF tests, it is necessary to know how emissivity varies with four different parameters; (1) wavelength, (2) viewing angle, (3) temperature, and (4) surface condition, for a wide range of basic materials. Information concerning emissivity versus each one of these variables with the others held constant is available in the scientific literature for many materials and need only be collected, evaluated, and put in a conveniently useful format. With this information at hand, the TFTF staff could provide all emissivity input necessary to make front surface temperature measurements for many test situations. When new materials are being tested, it will usually not be possible to use extrapolated emissivity values.

Step 3. Measuring Emissivities.

For thermal tests of newly developed materials, emissivity measurements may be either necessary or desirable. These measurements can be performed in conjunction with thermal test capabilities which are provided the users. Equipment required for both of the recommended emissivity and reflectivity measurements is: (1) a spherical blackbody source with 50 mm (~2 inch) aperture, (2) the pyrometer

and recording equipment used for materials testing, and (3) a mechanical structure to position the specimen and radiation thermometer relative to the blackbody. The same radiation thermometer and data recorders used for material testing will be used for this emissivity measurement.

When it is necessary to measure test specimen emissivities which are higher than approximately 0.7, the cooling rate method should be used. To determine emissivity by the cooling rate method, the specimen is first heated to a known temperature by allowing it to come to equilibrium in a spherical blackbody furnace. The specimen is then removed from the furnace to a cool environment and several apparent temperature readings are taken as the specimen cools. These data points are extrapolated to the time the specimen was removed from the furnace to give the apparent temperature which coincides with the known blackbody temperature of the furnace and hence the emissivity correction necessary to convert the apparent temperature to the blackbody temperature.

Many materials tested for thermal survivability have characteristically low emissivities. An excellent method for measuring low values of emissivity is to measure reflectivity and use the relationship $E + R = 1$ for opaque materials.

With the pyrometer in position on the support mechanism but with the specimen removed, a reading of the signal from the blackbody furnace is recorded. The specimen is put in place on the support between the furnace and the pyrometer so it fills the pyrometer field of view. Another reading is then taken which represents the signal from the cool (ambient temperature) specimen. These support mechanisms with the thermometer and specimen are then moved toward the blackbody source until the specimen is well inside the sphere where another pyrometer reading is quickly recorded. Because the specimen has not had time to change temperature appreciably, this reading represents the radiant energy reflected from the specimen surface when the full radiant flux of the blackbody furnace is incident upon it. The ratio of this pyrometer measurement to the first measurement of the blackbody signal corresponds to the definition of reflectivity, i.e., the ratio of the radiant energy reflected from a surface to that arriving at the surface. This ratio may require some small correction for the ambient temperature pyrometer reading.

Using this method the $R = 1 - E$ is measured in the wavelength band desired because the same instrument is used for both reflectivity and temperature measurements. The measurement is also made at the proper viewing angle. The specimen prepared for emissivity measurement can be an exact duplicate of the one used for thermal testing except for its linear dimensions. Only the temperature of the reflectivity measurement must be different than is used in the actual test and reflectivity does not change rapidly with temperature for a fixed wavelength band.

Using this procedure the emissivity of surfaces can be measured, both before and after thermal testing if desired.

By following these three steps all problems of emissivity associated with non-contact, front surface temperature measurements at the TFTF can be resolved satisfactorily. Some library research and user indoctrination is required before the Step 2 procedure is used and the additional laboratory equipment is required to perform the measurements described in the Step 3 procedure.

B-4 TABLE OF EMISSIVITIES APPLICABLE TO GP SERIES THERMOMETERS

For metals with smooth, clean (unoxidized) surfaces emissivities are usually in the range 0.05 to 0.50 and are usually very wavelength dependent, being higher at shorter wavelengths. The appropriate settings for Series GP1, GP2, and GP3 LAND thermometers are given in Table B-1 which is reproduced from product literature by Land Instruments Inc., Tullytown, PA. It must be remembered that these are guideline figures. They can be substantially increased if the surface is rough or even slightly oxidized.

If a more precise emissivity value is required, it can be obtained by an

- on-site spot check of true temperature either by a LAND surface pyrometer (for solids) or an immersed thermocouple (liquids), and adjustment of the emissivity control to make the indicated temperature equal the true temperature; or

- by a laboratory experiment.

Where no value is given this is because either the thermometer is not suitable for the measurement or its minimum temperature is too high. Thus, the DPI series is for glass surface temperature measurement: the GPI has a minimum temperature 450°C so that paper and wood etc. cannot be measured.

Table B-1. Table of emissivities for Land GP series thermometers.

Metals

Material		Emissivity for Thermometer Series		
		GP1	GP2	GP3
Aluminum		0.13	0.09	0.025
	oxidized	0.40	0.40	0.35
Chromium		0.43	0.34	0.07
	oxidized	0.75	0.80	0.85
Cobalt		0.32	0.28	0.04
	oxidized	0.70	0.65	0.35
Copper		0.06	0.05	0.03
	oxidized	0.80	0.80	0.80
Gold		0.05	0.02	0.02
Iron and Steel		0.35	0.30	0.10
	oxidized	0.85	0.85	0.80
Lead		0.35	0.28	0.13
	oxidized	0.65	0.65	0.65
Magnesium		0.27	0.24	0.07
	oxidized	0.75	0.75	0.75
Molybdenum		0.33	0.25	0.10
	oxidized	0.80	0.80	0.80
Nickel		0.35	0.25	0.04
	oxidized	0.85	0.85	0.85
Palladium		0.28	0.23	0.05
Platinum		0.27	0.22	0.07
Rhodium		0.25	0.18	0.05
Silver		0.05	0.04	0.02
	oxidized	0.10	0.10	0.10
Tantalum		0.35	0.20	0.08
	oxidized	0.80	0.80	0.80
Tin		0.40	0.28	0.28
	oxidized	0.60	0.60	0.60
Titanium		0.55	0.50	0.15
	oxidized	0.80	0.80	0.80
Tungsten		0.39	0.30	0.06
Zinc		0.50	0.32	0.04
	oxidized	0.60	0.55	0.30

Table B-1. Table of emissivities for Land GP series thermometers. (continued)

Alloys

Material	Emissivity for Thermometer Series		
	GP1	GP2	GP3
Brass	0.20	0.18	0.03
oxidized	0.70	0.70	0.60
Chromel & Alumel	0.30	0.30	0.30
oxidized	0.80	0.80	0.80
Constantan & Magnesium	0.25	0.22	0.05
oxidized	0.65	0.60	0.35
Inconel	0.30	0.30	0.10
oxidized	0.85	0.85	0.85
Monel	0.25	0.22	0.10
Nichrome	0.30	0.28	0.20
oxidized	0.85	0.85	0.85

Refractories

Material	Emissivity for Thermometer Series		
	GP1	GP2	GP3
Alumina	0.30	0.30	0.60
Brick			
red	0.80	0.80	0.90
white refractory	0.30	0.35	0.80
silica	0.55	0.60	0.80
sillimanite	0.60	0.60	0.60
Ceramics	0.40	0.50	0.90
Magnesite			0.60

Table B-1. Table of emissivities for Land GP series thermometers. (Concluded)

Miscellaneous

Material	Emissivity for Thermometer Series				
	GP1	GP2	GP3	DP1	DP2
Asbestos - board, paper or cloth	0.90	0.90	0.90		
Asphalt	0.85	0.85	0.85		
Carbon graphite soot	0.85 0.80 0.95	0.85 0.80 0.95	0.85 0.80 0.95		
Cement & Concrete	0.65	0.7	0.90		
Cloth - all types, close weave open weave reduces emissivity	0.75	0.80	0.85		
Glass 3 mm thick 6 mm thick 12 mm thick 20 mm thick				0.96 0.96 0.96 0.96	0.72 0.90 0.95 0.96
Paper & Cardboard			0.8 - 0.95		
Plastics - opaque transmission 0.1 transmission 0.4			0.85 0.75 0.45		
Paints - oils and enamels laquers aluminium			0.90 0.85 0.3 - 0.6		
Rubber - hard, black soft, grey			0.95 0.85		
Water - depth greater than 50 mm			0.95		
Wood			0.85		

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